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**N91-22658****THE NASA ER-2 METEOROLOGICAL MEASUREMENT SYSTEM:  
INSTRUMENTATION, CALIBRATION AND INTERCOMPARISON RESULTS**K. Roland Chan<sup>1</sup>, Stuart W. Bowen<sup>2</sup>, Stan G. Scott<sup>1</sup>, and T. Paul Bui<sup>1</sup>

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**Abstract**

The NASA ER-2 aircraft is used as a platform for high-altitude atmospheric missions. The Meteorological Measurement System (MMS) was designed specifically for atmospheric research to provide accurate, fast-response, in situ measurements of pressure ( $\pm 0.3$  mb), temperature ( $\pm 0.3^\circ\text{C}$ ), and the 3-dimensional wind vector ( $\pm 1\text{ m s}^{-1}$ ). Developed over a period of years and operational since early 1986, the MMS has participated in three major scientific expeditions: the Stratospheric-Tropospheric Exchange Project (STEP) based in Darwin, Australia in January and February of 1987, the Airborne Antarctic Ozone Experiment (AAOE) based in Punta Arenas, Chile in August and September of 1987, and the Airborne Arctic Stratospheric Expedition (AASE) based in Stavanger, Norway in January and February of 1989.

The MMS consists of three subsystems: (1) an air motion sensing system to measure the velocity of the air with respect to the aircraft, (2) a high-resolution inertial navigation system (INS) to measure the velocity of the aircraft with respect to the earth, and (3) a data acquisition system to sample, process and record the measured quantities. The location of the MMS instrumentation is shown in Fig. 1. Detailed discussion of the instrumentation is reported by Scott et al. [1989].

(1) The air motion sensing system consists of sensors which measure pressures, temperature, and airflow angles (angle of attack and angle of sideslip). Static and total pressure measurements are obtained from precision pressure transducers, using existing aircraft pressure ports and plumbing. Total air temperature is obtained from two total temperature probes with matching signal conditioners installed on the lower hatch of the equipment bay. A radome differential pressure system, similar to the one developed for a NASA Convair-990 aircraft [Chaussee et al., 1983; Bowen et al., 1985], is installed in the ER-2 aircraft to measure the airflow angles.

(2) The inertial navigation system normally used by the ER-2 aircraft is a Litton LTN-72 INS. While this INS is satisfactory for aircraft navigation, it does not meet the stringent requirements of data rate and accuracy for MMS measurements. With a standard INS, the accuracy of wind computation is adversely affected by the internal digital filters of the INS, and the resolution is limited by the INS data bus update rate of only  $3\text{ s}^{-1}$ . A high-resolution Litton LTN-72RH INS, configured for scientific applications, was selected for the MMS because of its compatibility (with the aircraft installation), higher altitude specification (usable up to cabin pressure altitude of 26,000

ft), precision (no digital filters), time resolution (data update rate of  $25 \text{ s}^{-1}$ ), and special provisions for MMS measurements (vertical velocity and inertial altitude with internal baro-inertial loop). This INS is installed in the aircraft upper equipment bay, which is maintained at  $\approx 28,000$ -ft pressure altitude when the aircraft is at 65,000 ft. Temperature in the equipment bay with a full complement of operating equipment is typically 5 to  $25^\circ\text{C}$ .

(3) The data acquisition system (DAS) samples 45 independent variables at a rate of  $5 \text{ s}^{-1}$  (maximum:  $10 \text{ s}^{-1}$ ), accommodates various modes of data (analog and digital, serial and parallel, synchronous and asynchronous), stores the data on two media (disc and tape), and meets aircraft constraints of compactness, light weight, and safety. Commercially available board products were utilized where possible. The DAS is installed in the upper equipment bay of the aircraft, next to the inertial navigation unit. Major components of the DAS consist of a single-board computer, mass data storage systems, a communication and memory board, an INS receiver, clock and terminal interfaces, analog-to-digital (A/D) interfaces, input/output (I/O) interfaces, and power supplies.

The data acquisition software is highly customized and modularized to meet the following requirements: flexibility in modifying the data frame and sampling rate ( $1$  to  $10 \text{ s}^{-1}$ ); redundancy of mass data storage (tape and disc); simultaneity of sampling 45 variables ( $< 0.01 \text{ s}$  between the first sampled variable and the last); asynchronous interface with INS digital data streams; control of disc turn-on and turn-off during landing and takeoff to avoid possible damage to the disc drive; handling of read/write errors to minimize data loss; handling of data logging in case of temporary power malfunction; and special utility and diagnostic programs for preflight checkout and postflight command. Software is a key element of the MMS; it was written in the MC68000 microprocessor assembly language for compactness and speed. The data acquisition software code size is 34 Kbytes.

The DAS has two operating modes: stand-alone (flight mode) and interactive (ground mode). In the flight mode the DAS runs the acquisition routine at power turn-on and logs data continuously. Pilot interaction is limited to a power on-off switch in response to a fail-light indicator. In the interactive mode the user can execute any of the modular routines, including flight-mode acquisition, through an external terminal. Postflight data can be downloaded from the DAS to a ground system in two ways: through a heavily shielded and terminated parallel cable and through a pair of communication boards. The second method has a fast transfer rate of  $\approx 100 \text{ kBaud}$ . For an 8-hour flight, MMS raw data ( $\approx 15 \text{ Mbytes}$ ) can be downloaded to the ground station in 15-20 min. The MMS ground station consists of several portable and desktop computers. Our current research effort has been primarily in the development and improvement of the data analysis software.

The calibration of the MMS instrumentation consists of (1) sensor calibration, (2) system and transducer response tests, (3) inflight calibration, and (4) laboratory INS calibration. First, pressure and temperature sensors, signal conditioners, transducers are individually and periodically calibrated either in-house or by the manufacturer. Second, the frequency response of the radome

differential pressure system was measured and determined to be satisfactory even at high altitudes in the range of interest up to 10 Hz. The dynamic response of the radome system, including the short feeder tubing, has been measured in the laboratory. Third, inflight calibration requires the pilot to fly the aircraft in square patterns and to induce yaw and angle-of-attack maneuvers at several altitudes. These inflight maneuvers are used to establish the calibration constants of the differential pressure system which measures the airflow angles and to determine the angular offset between the differential pressure system and the INS. The calibration constants are Mach-number (0.35 - 0.72) dependent. Finally, the calibration of the INS is conducted on a physical pendulum of  $\approx 2$  m in length. The pendulum is tilted and positioned in such a way that pitch, roll, heading, N-S velocity, E-W velocity, and vertical acceleration can all be measured in each swing. Various time delays are introduced in the data processing, and Lissajous diagrams for each INS variable are plotted. This calibration procedure can determine the time delay of each INS output variable to the nearest 0.01 s. For the Litton LTN-72RH INS, there is  $\approx 0.045$  s time delay for the heading signal,  $\approx 0.39$  s for the vertical accelerometer output,  $\approx 0.08$  s for N-S and E-W velocities, and none for the pitch and roll signals. Time delays, caused by the INS internal electronics and/or the external antialiasing filters of the DAS, have been determined in the laboratory, and the appropriate time shift is applied to the data stream of each MMS measured variable during processing.

Intercomparison of MMS measurements, Vaisala radiosonde observation, and radar tracking data was conducted in April 1986 at the Crows Landing facility in California. Data were processed so that time and altitude of the three sets of data were properly matched. Measurements of pressure, temperature and the horizontal wind vector by the MMS, balloonsonde and radar were compared. The difference between the mean MMS and balloonsonde/radar measurements is within the specified accuracy of the instruments; the variability of these measurements is larger than the difference of the mean. The variability is primarily due to spatial and temporal difference between the aircraft and the balloons. This intercomparison indicates that the overall MMS accuracy is very good.

The vertical wind is the most difficult measurement of the MMS. As an illustration of the MMS response to a significant natural atmospheric phenomenon, the vertical wind measurement on September 22, 1987 during the AAOE mission is shown in Fig. 2. The ER-2 aircraft was stationed at Punta Arenas, Chile ( $53^{\circ}\text{S}$ ,  $72^{\circ}\text{W}$ ), flew southward on an isentropic surface ( $\approx 420\text{K}$ ), descended and ascended at the southern terminus ( $\approx 72^{\circ}\text{S}$ ) over Antarctica, and returned northward on the same isentropic surface. The vertical wind measurement over the 6-hour period is shown in Fig. 2a with time and corresponding latitude indicated on the bottom and top of the figure, respectively. For most of the flight the atmosphere was smooth, and vertical winds generally average to zero over any section of the flight. However, large perturbations are observed on both the southbound and northbound legs at  $\approx 69^{\circ}\text{S}$  latitude. These perturbations have been noted as possible mountain lee waves over the Antarctic Palmer Peninsula [Chan et al., 1989; Gary, 1989]. Two 20-min sections

of the data in Fig. 2a are shown in Fig. 2b and 2c with the time scale expanded. In Fig. 2b (58,000 - 59,200 s) the amplitude of the vertical wind is very small and close to zero throughout this 20-min period. In Fig. 2c (58,000 - 59,200 s), the mountain lee wave signature is shown in more detail. Although the amplitude of the vertical wind data has large excursions during this 20-min period, the vertical wind measurement is well defined and returns to the mean value after the perturbation.

The MMS meets the science requirements for in situ airborne measurements of free-stream pressure, temperature and wind for atmospheric missions. The customized DAS provides the flexibility to adapt the MMS to changing scientific needs. Special attention has been given to sensor and system calibrations. Future development will involve spectral analyses of MMS variables to further reduce the aircraft motion feed-through in the wind measurement and computation.

### References

- Bowen, S. W., S. G. Scott, K. R. Chan, and J. G. Borucki, Yaw and angle of attack measurements on the CV-990 aircraft, Paper 85-0341, *AIAA 23rd Aerospace Science Meeting*, Reno, NE, 1985.
- Chan, K. R., S. G. Scott, T. P. Bui, S. W. Bowen, and J. Day, Temperature and horizontal wind measurements on the ER-2 aircraft during the 1987 Airborne Antarctic Ozone Experiment, *J. Geophys. Res.*, **94**, 11573-11587, 1989.
- Chaussee, D. S., P. G. Buning, and D. B. Kirk, Convair 990 transonic flow-field simulation about the forward fuselage, Paper 1785, *AIAA Applied Aerodynamics Conference*, Danvers, MA, 1983.
- Gary, B. L., Observational results using the microwave temperature profiler during the Airborne Antarctic Ozone Experiment, *J. Geophys. Res.*, **94**, 11223-11231, 1989.
- Scott, S. G., T. P. Bui, K. R. Chan, and S. W. Bowen, The Meteorological Measurement System on the NASA ER-2 aircraft, submitted to *J. Atmospheric and Oceanic Technology*, 1989.

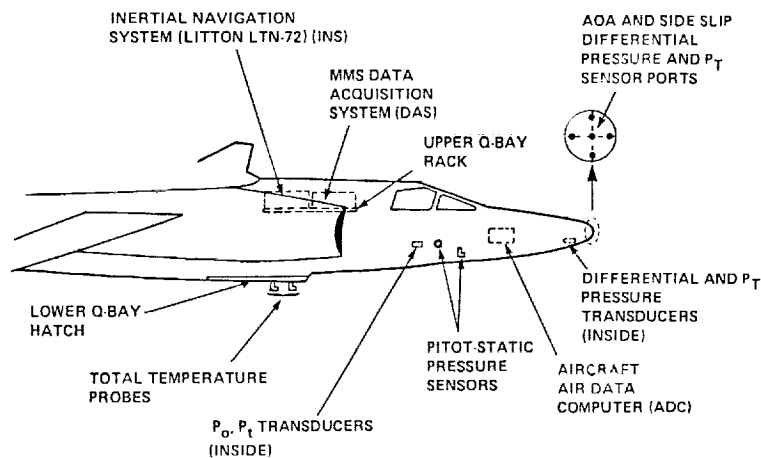


Fig. 1. Location of the MMS instrumentation on the ER-2 aircraft.

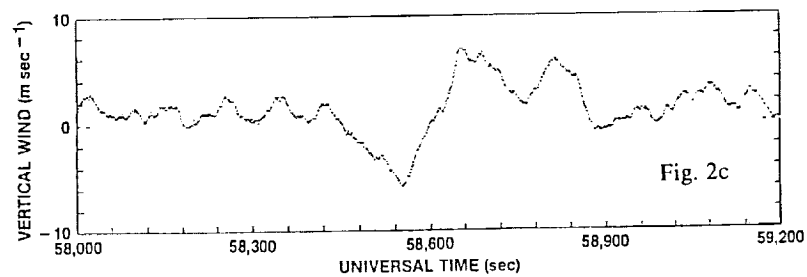
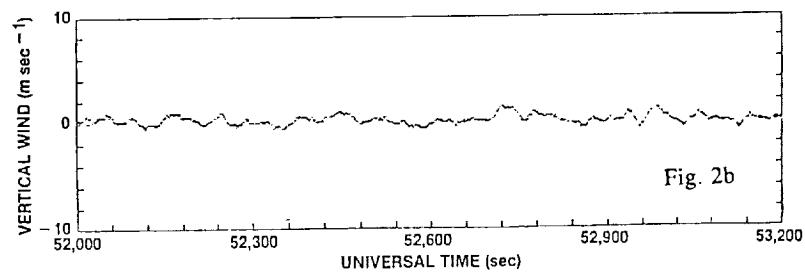
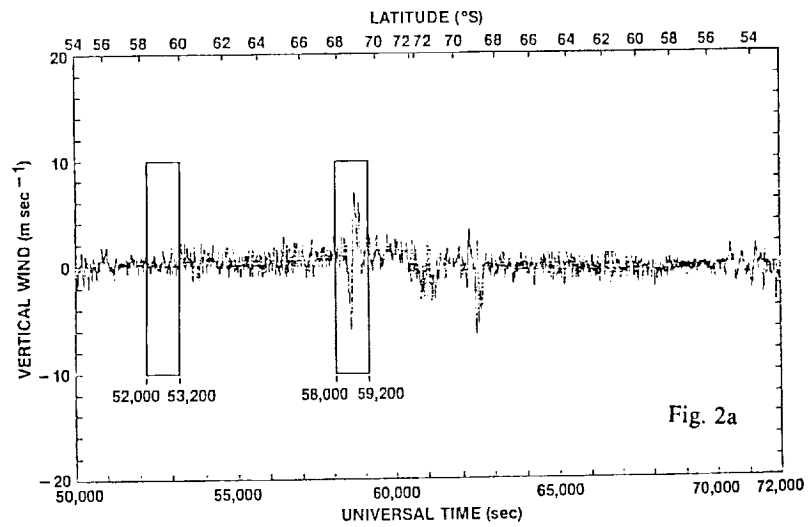


Fig. 2a. Vertical wind results on September 22, 1987 during the Airborne Antarctic Ozone Experiment (AAOE) mission.  
 Fig. 2b. Expanded section (52,000 - 53,200 s) of Fig. 2a.  
 Fig. 2c. Expanded section (58,000 - 59,200 s) of Fig. 2a.